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HIGH AVERAGE POWER ACTIVE TRACKER LASER TECHNOLOGY

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ABSTRACT

Through the Phillips Laboratory's *Active Tracker Laser* (ATLAS) program, high average power, high pulse repetition frequency diode-pumped solid-state laser technology has been under development since 1992. A solid-state laser illuminator requirement was generated, in support of the Ground Based Laser Technology program, for closed loop tracking of actively illuminated low Earth orbit satellites. As a result of this laser technology development effort, high brightness laser sources at both 1.064 μm and 532 nanometers have been developed and demonstrated.

1.0 INTRODUCTION

In 1992, the Phillips Laboratory's Ground Based Laser Technology (GBLT) Program generated a requirement for a diode-pumped solid-state laser to support active tracking of low Earth orbit satellites. The laser's performance parameters were dictated by GBLT experiments requirements. Average output power, laser wavelength, pulse energy, pulse repetition frequency, temporal pulse profile, far-field spatial pulse profile, laser beam divergence, and temporal coherence length were all important in driving the laser conceptual designs in a specific direction. Additionally, though not as important, it was desirable that the laser be capable of having a frequency doubled output. Issues related to average power scaling, compact packaging, wallplug efficiency and space qualification were also important in the overall design effort.

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Abstract

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The initial laser performance specifications required development of a diode-pumped solid-state laser brassboard with a wavelength near 1 micron, a pulse repetition frequency between 2.5 and 4 kilohertz, a laser output divergence less than twice the diffraction limit, a temporal coherence less than 10 centimeters, and a total average output power exceeding 1 kilowatt. Because of the long optical propagation ranges involved, from several hundred kilometers to more than a thousand kilometers, existing high average power solid-state lasers in 1992 did not have sufficiently good beam divergence to deliver adequate photons to targets for active tracking experiments. This, combined with the pulse repetition frequency requirement, drove initial conceptual designs from flashlamp-pumped solid-state lasers to diode-pumped solid-state lasers. It is difficult to pulse flashlamps with the required pump pulse format at multiple kilohertz pulse repetition frequencies. Additionally, because of their narrow pump spectrum (few nanometers), laser diode pump arrays provide several times less thermal loading in solid-state gain media than flashlamps; this, in turn, can dramatically improve a solid-state laser's beam divergence by reducing the magnitude of thermally-induced aberrations in the gain media.

Four *Active Tracker Laser* (ATLAS) contracts were awarded during 1993 and 1994 for diode-pumped solid-state laser risk reduction. In late 1994, two contractors were selected to continue research and development, one of which was designated to deliver a fully operational, high average power laser brassboard to the Phillips Laboratory's Starfire Optical Range for GBLT experiments. This laser was delivered in January 1997 and is currently undergoing characterization and testing.

2.0 LASER TECHNICAL REQUIREMENTS

As stated previously, there were seven basic technical performance requirements for the ATLAS brassboard: wavelength, pulse repetition frequency, average output power, beam quality, coherence length, far-field beam spatial profile, and temporal pulse profile. These criteria drove the laser design. In turn, these criteria were driven by Air Force GBLT experiment requirements.

The wavelength technical specification was driven by sensor technology and available high power solid-state laser gain materials. The most well developed, robust gain medium is Neodymium-doped Yttrium-Aluminum-Garnet (Nd:YAG), which has its primary spectral emission line at 1.064 microns. The most advanced, currently available sensors are optimized in the near infrared. These two factors drove the wavelength to ~1 micron.

The pulse repetition frequency (PRF) technical specification was driven by both the active tracking requirements and available track sensor technology. For example, given a laser pulse propagating from the ground to a 300 kilometer altitude and then reflecting back to a track sensor on the ground near the laser source, the round trip time is approximately 2 milliseconds. This corresponds to a maximum laser PRF of less than 500 Hz unless appropriate measures are taken to suppress the effects of scattered light from the outgoing laser pulse on the track sensor. This scattered light, which can be a much larger signal to the track sensor than the light reflected or scattered from the object in orbit at several hundred kilometers range, can come from optical surface reflections and optical scattering from atmospheric aerosols. As the range to the satellite is increased, the maximum bandwidth is further reduced, but this is in part compensated for by the decreased slew requirement on the track sensor telescope gimbal. To adequately support GBLT tracking requirements, the laser PRF was required to be between 2.5 and 4.0 kHz, which was within the capabilities of existing track sensor technology.

The average output power technical specification was driven by the track sensor closed-loop bandwidth, the laser pulse energy requirement, and the laser beam divergence (beam quality) requirement. The track sensor has a minimum signal-to-noise requirement which, in conjunction with optical train losses, atmospheric transmission losses and laser beam divergence, determines the minimum acceptable laser illuminator pulse energy. This required energy, combined with the required laser PRF and laser beam divergence, determines the required total average power.

The beam quality or beam divergence technical specification was driven by the target range and the laser brassboard's projected average power scalability. As shown below, improving the beam quality can have a dramatic effect on the laser's average power requirement.

After the initial contract awards, it became evident that the original specifications, while accurate, were unnecessarily restrictive. The average power and beam divergence were requirements in the original performance specifications, but what is more important is how many photons actually reach the target. This is where beam divergence or beam quality is recognized as the more important of the two specifications for this application, and with this recognition comes a revision of the original specification; it can be rewritten in terms of laser beam brightness [1].

We wanted the laser to meet a brightness specification which was greater than or equal to that which could be achieved by a 1 kW average power laser which was ≤ 2 times diffraction limited. Brightness, B, is defined as

$$B = \frac{P_0}{A\Omega} = \frac{P_0}{A\left(4\lambda^2/A\right)} = \frac{P_0}{4\lambda^2} \ , \tag{1}$$

where P_0 is the average power within the far-field aperture defined by the first null of a diffraction-limited beam, A is the near-field aperture area, and Ω is the solid angle subtended by the far-field aperture. For a diffraction-limited laser with a rectangular, uniformly-filled aperture, the solid angle Ω is $(4\lambda^2/A)$, where λ is the laser wavelength and A is the near-field aperture area. Since both A and λ are fixed, P_0 must also be fixed (or increase) to maintain the required brightness as defined above. For a diffraction-limited beam emitted from a rectangular aperture, approximately 82 percent of the laser's output power is contained in the central lobe:

$$P_{0(DL)} = 0.82P_{TOTAL} \ , \tag{2}$$

where P_{TOTAL} is the total power through aperture A. For a ≤ 2 times-diffraction-limited (2 xDL) beam, the brightness is required to be $\geq \frac{1}{4}B_{DL}$, where B_{DL} is the diffraction-limited beam brightness. The power in the "diffraction-limited" far-field aperture for this beam will be

$$P_{0(2xDL)} = \frac{P_{0(DL)}}{(BQ)^2} = \frac{P_{0(DL)}}{4} = \frac{0.82P_{TOTAL}}{4} \ , \tag{3}$$

where "BQ" is the laser's "times diffraction limited" beam quality. For P_{TOTAL} = 1000 Watts, $P_{0(2xDL)}$ = 205 Watts. To maintain an equivalent brightness, $P_{0(2xDL)}$ must remain constant (or increase). This means that for decreasing laser output power (P_{TOTAL}), the beam quality (BQ) must improve:

$$BQ \le \sqrt{\frac{0.82P_{TOTAL}}{P_{0(2xDL)}}} = \sqrt{\frac{0.82P_{TOTAL}}{205}} \quad , \tag{4}$$

where P_{TOTAL}, as defined previously, is the measured power in Watts through aperture A.

Using the definition for laser beam brightness instead of an average output power and beam divergence allowed us to meet the system level requirements from two approaches: increasing average power while maintaining a constant beam quality or improving beam quality while maintaining a constant average power. We can also vary both parameters to optimize the beam brightness. Equation (4) above allows us to generate a constant brightness curve for the laser of interest. Figure 1 is a plot of the constant brightness curve for the TRW ATLAS brassboard. Any combination of average power and

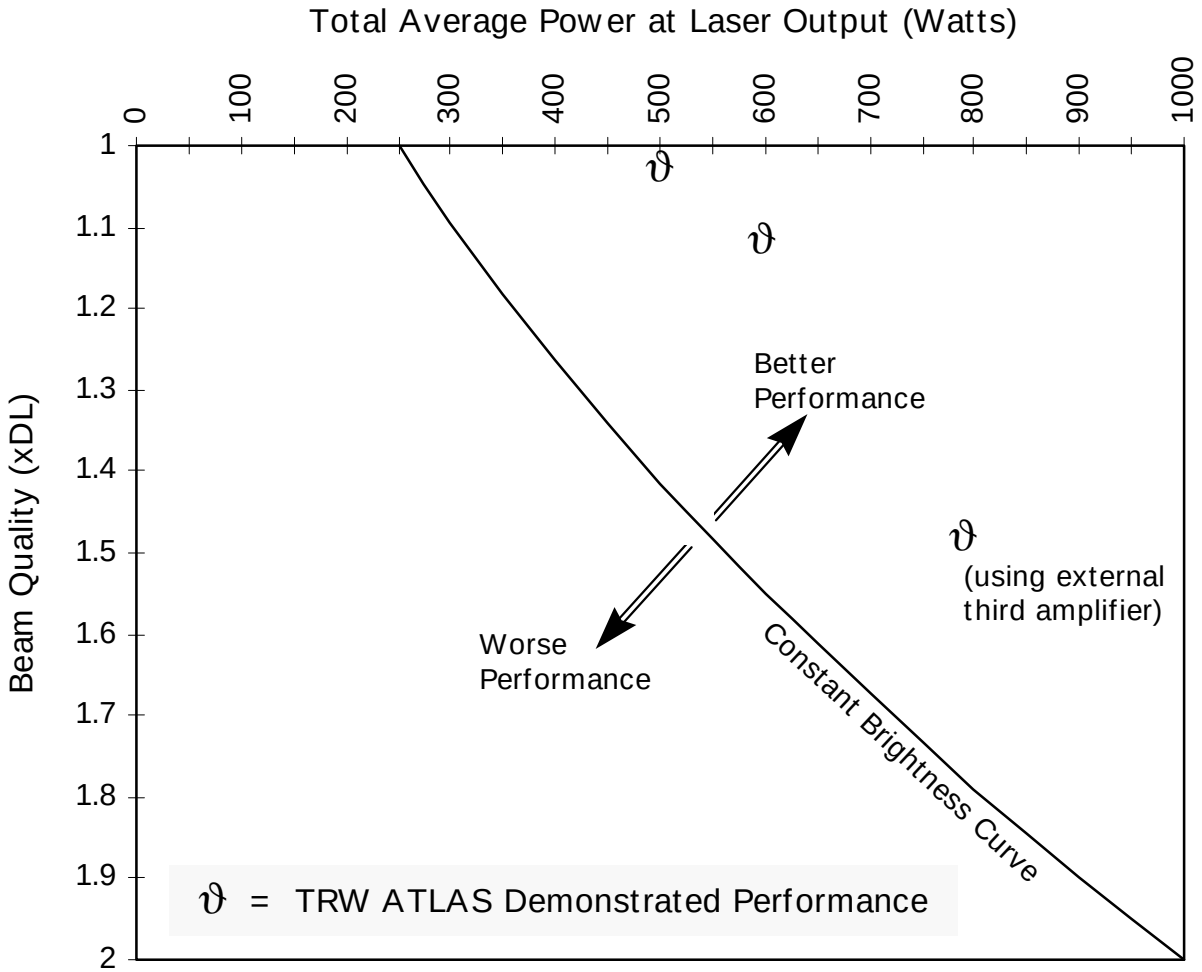

Figure 1: Constant brightness curve for TRW ATLAS brassboard.

beam quality which is to the right of the curve is an improvement over our original specification, and anything to the left of the curve is worse. On the plot are experimental data points which show that the delivered laser brassboard has exceeded our brightness requirement and, therefore, performs better than

any laser meeting the original specifications. The combination of moderate decrease in average power and significantly improved beam quality provided a much brighter laser source than originally specified.

3.0 LASER BRASSBOARD DESCRIPTION

As shown in Figure 2, the Active Tracker Laser brassboard which was delivered to the Phillips Laboratory's Starfire Optical Range is a phase conjugated master-oscillator-power-amplifier (MOPA) configuration using laser-diode-pumped Nd:YAG slabs in both the oscillator and amplifiers. An optical isolator and beam shaping telescope are located between the oscillator and amplifiers. Relay imaging telescopes were used in the amplifier train to enhance the laser beam quality and minimize Fresnel losses. A stimulated Brillouin scattering (SBS) cell was used as a phase conjugate reflector to double-pass the amplifiers; this technique was used to ensure minimal beam quality degradation through the

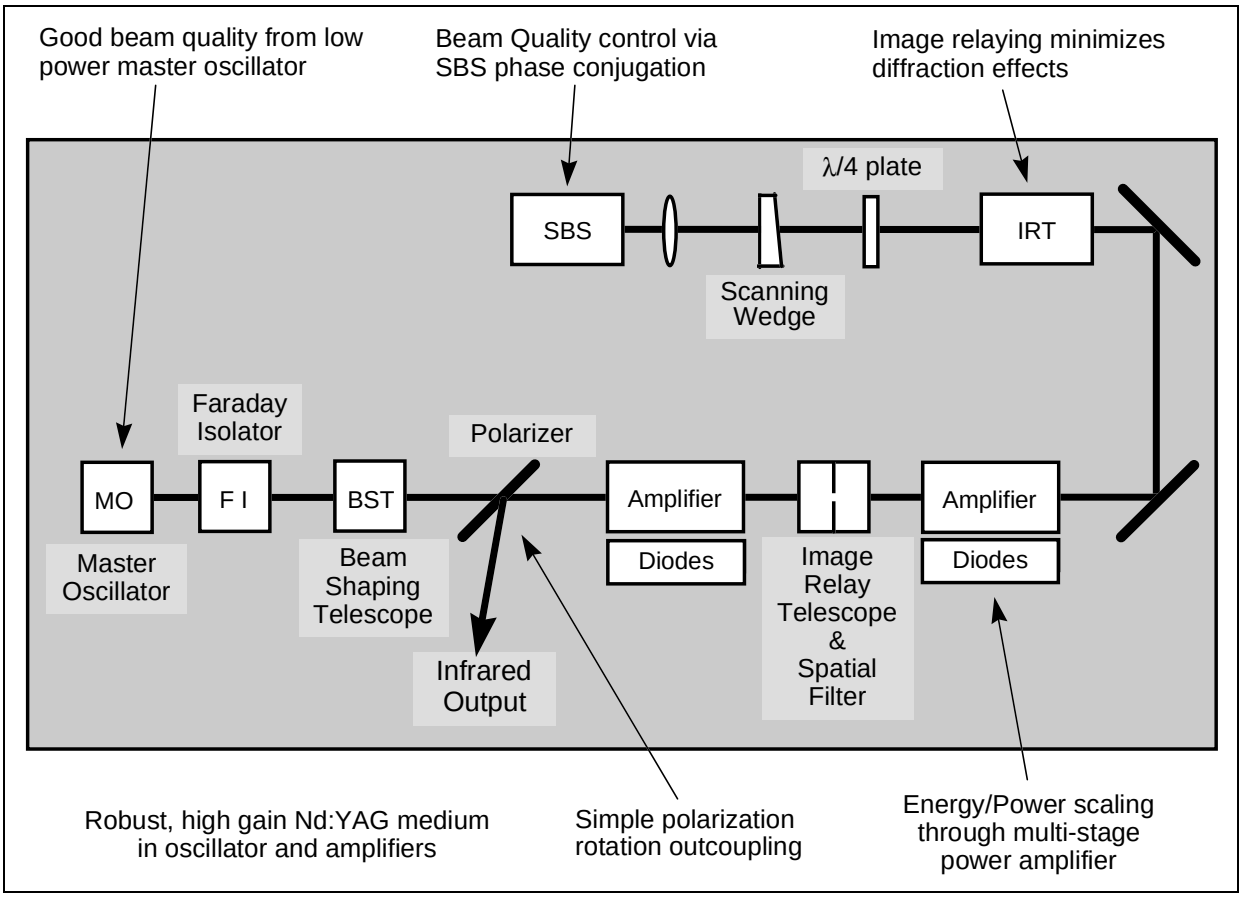

Figure 2: TRW Active Tracker Laser (ATLAS) brassboard optical schematic.

amplifiers and amplifier optics while retaining both system output power and system efficiency. The master oscillator is injection-seeded to maintain a long coherence length pulse with a smooth temporal profile, which is desirable for optimal SBS wavefront reversal and reflectivity. The double-pass amplifier train is polarization outcoupled.

The Active Tracker Laser transmitter unit is approximately 8 cubic feet, and the laser electronics unit is housed in a standard 19 inch rack. Liquid-to-liquid heat exchangers are used to maintain the laser thermal environment at nominal operating temperatures. The primary side of the heat exchangers are interfaced to the Starfire Optical Range cooling plant. Figure 3 is the testbed layout used to measure the average power and beam quality of the ATLAS brassboard. Figure 4 is a photograph of the ATLAS brassboard with the cover removed from the laser transmitter unit. The laser has been installed at the Starfire Optical Range on Kirtland Air Force Base in New Mexico. It is currently undergoing testing and preliminary integration into the GBLT experiment testbed.

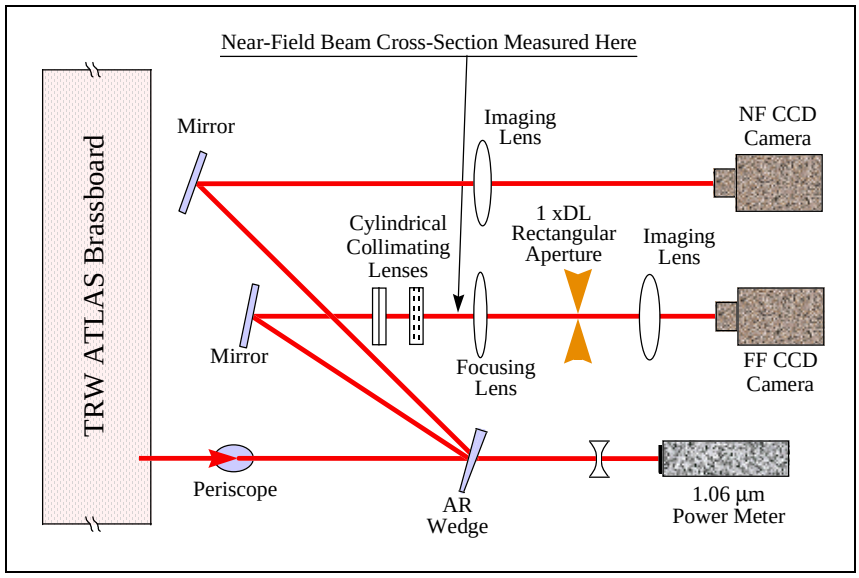

Figure 3: TRW ATLAS brassboard power/BQ characterization testbed.

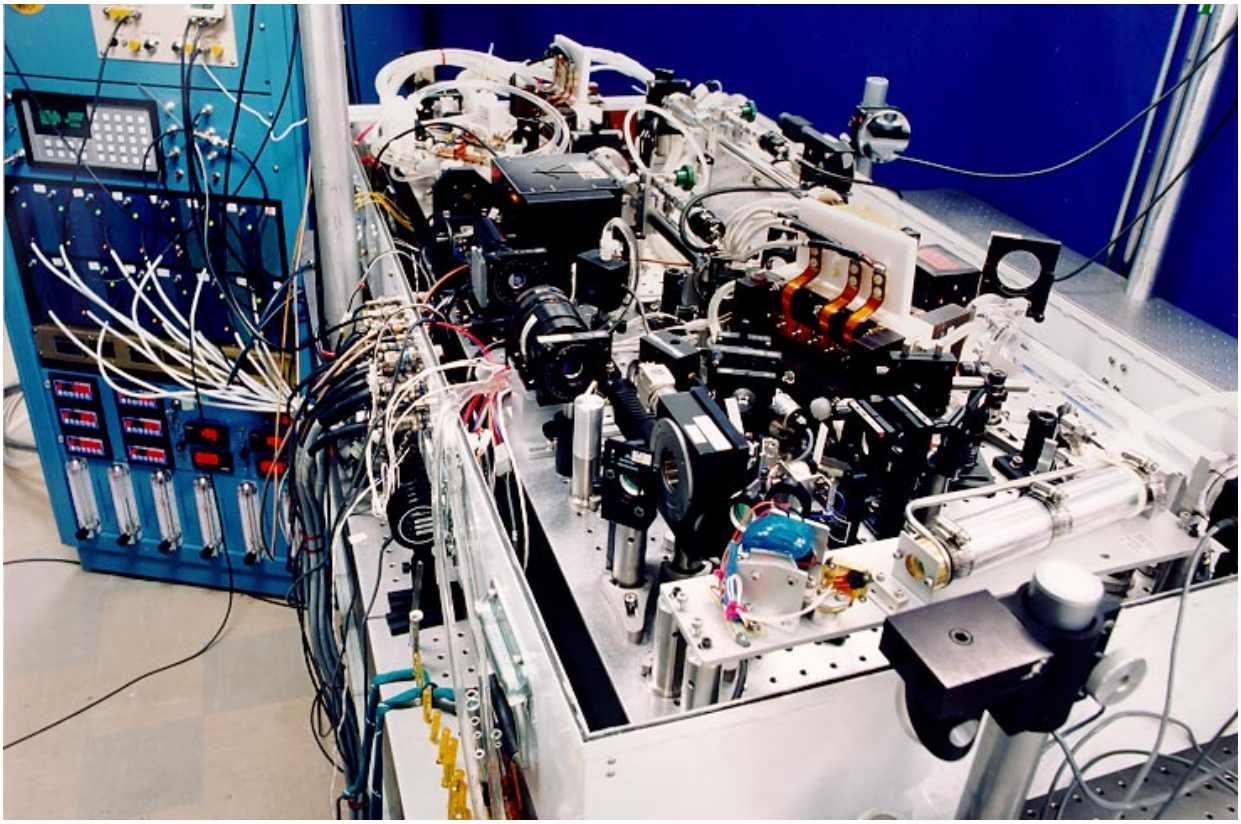
Figure 4: TRW ATLAS brassboard laser transmitter and electronics units.

4.0 ATLAS PERFORMANCE SUMMARY

The Air Force Phillips Laboratory's *Active Tracker Laser* (ATLAS) program has developed what is believed to be the world's brightest *Q*-switched, diode-pumped Nd:YAG laser. At 500 Watts output power at 2.5 kHz, the beam quality is approaching the diffraction limit (< 1.1 xDL). At 600 Watts output power at 2.5 kHz, the beam quality is ~1.1 xDL. When an external, single-pass, diode-pumped solid-state laser amplifier has been placed at the output of the ATLAS brassboard, 791 Watts output power at 2.5 kilohertz and a beam quality better than 1.5 xDL has been observed. Additionally, the ATLAS brassboard has been frequency doubled to 532 nanometers, achieving an average output power of 175 Watts (> 42 % conversion efficiency) at 2.5 kilohertz and with a beam quality of better than 1.5 times the diffraction limit. This is also believed to be the brightest frequency doubled Nd:YAG laser in the world.

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1. W. Koechner: *Solid-State Laser Engineering*, 4th edition, Springer Series in Optical Sciences, Vol. 1 (Springer-Verlag, Berlin 1996) p. 144.